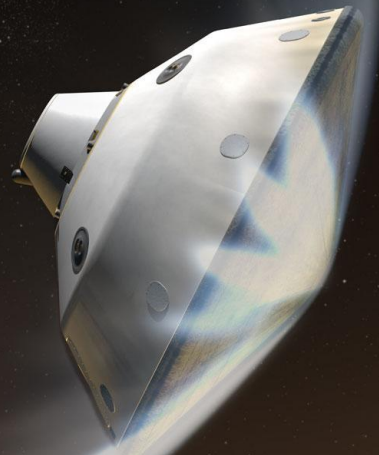
X-ray micro-tomography for advanced material technologies: a NASA perspective

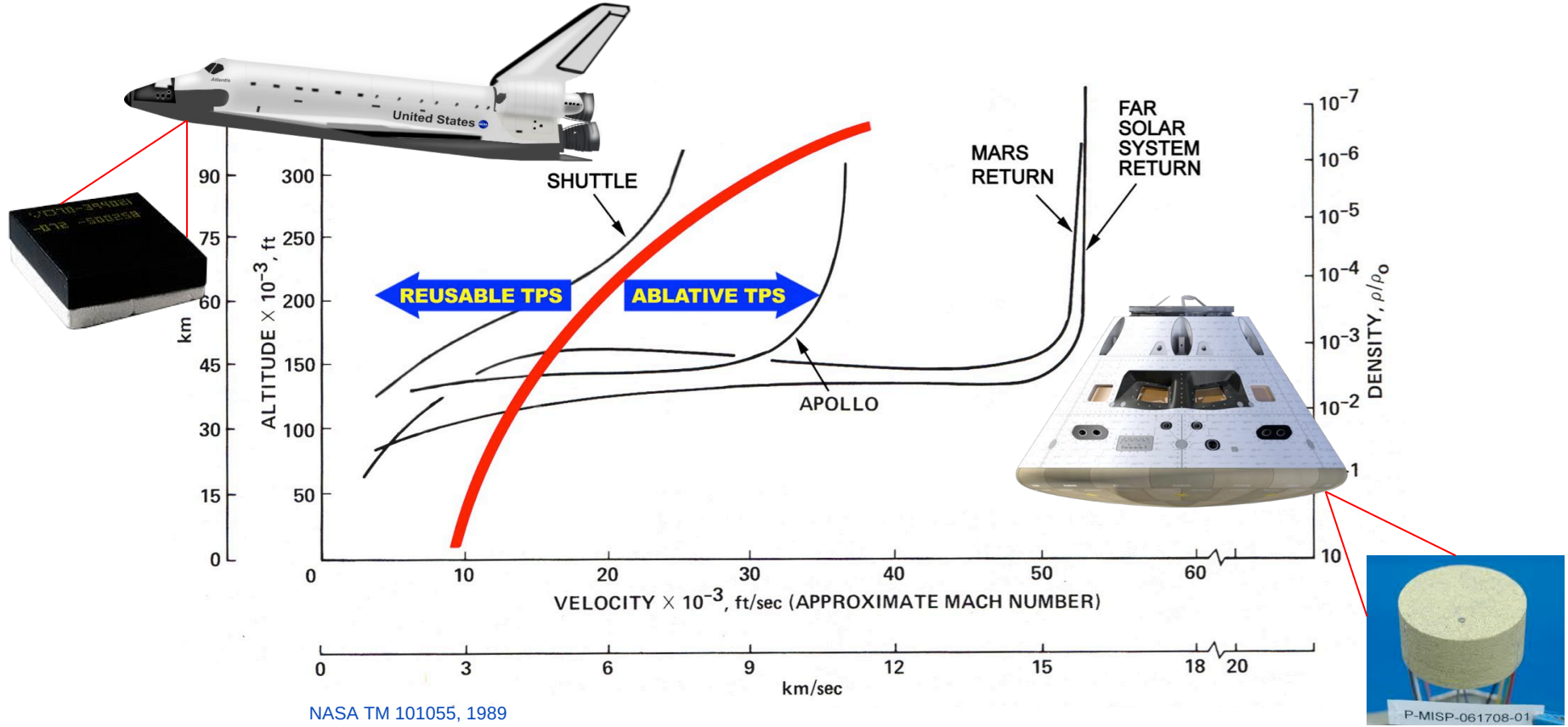


Joseph C. Ferguson [1]
Francesco Panerai [2]
Arnaud Borner [1]
Nagi N. Mansour [3]
Michael Barnhardt [3]
Michael Wright [3]

1. STC at NASA Ames Research Center
2. AMA at NASA Ames Research Center
3. NASA Ames Research Center

Space Tech Expo, 2017
Pasadena, CA

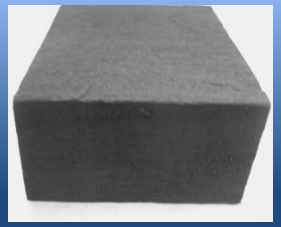
Thermal Protection Systems



NASA TM 101055, 1989

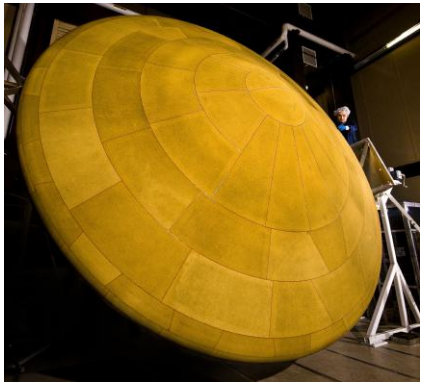
Ablative Thermal Protection Systems

Carbon fibers + Resin = PICA



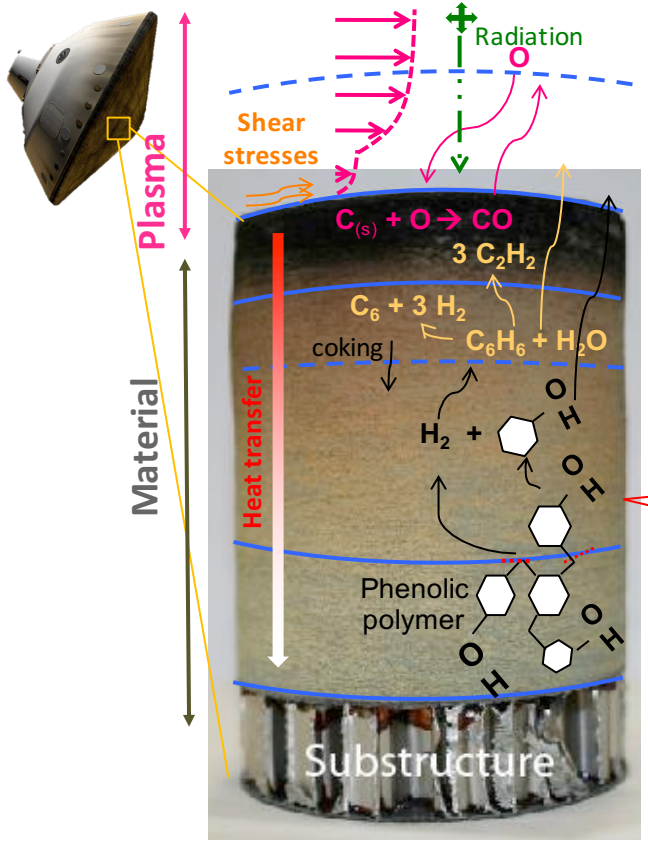
Stardust Capsule

Dragon V1 & V2



Mars Science Laboratory

Material Design and Modeling



Shock layer
≈ 6000 K

Boundary layer

≈ 3000 K

Ablation zone

≈ 1400 K

Coking zone

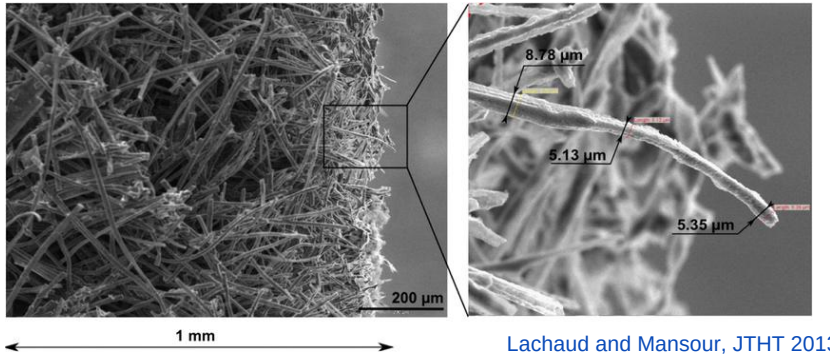
≈ 1200 K

Pyrolysis zone

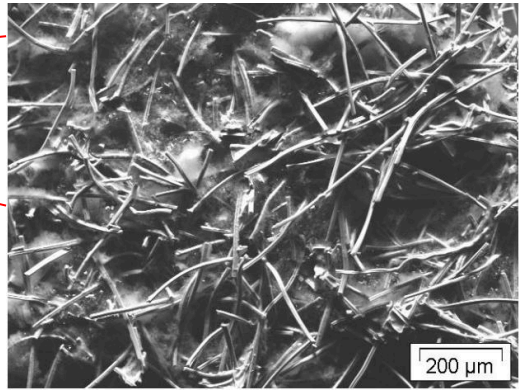
≈ 400 K

Virgin material

Bondline



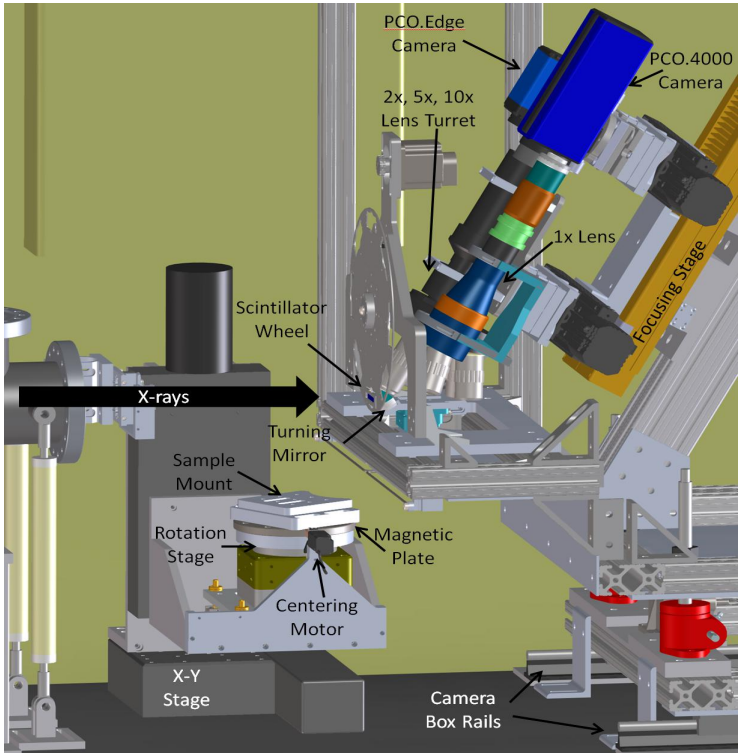
Lachaud and Mansour, JTHT 2013



Lawson et. al. 2010

X-ray micro-tomography

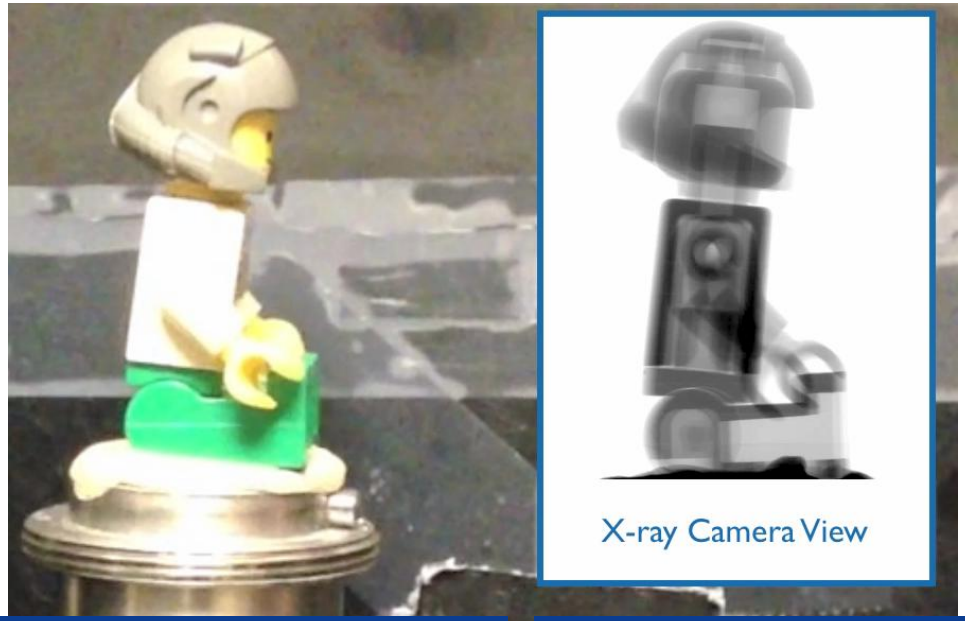
- Advanced Light Source (ALS) at the Lawrence Berkeley Natl. Laboratory
- Synchrotron electron accelerator used to produce 14Kev X-rays
- Used for many research areas, including optics, chemical reaction dynamics, biological imaging, and **X-ray micro-tomography**.



http://www2.lbl.gov/MicroWorlds/ALSTool

X-ray micro-tomography

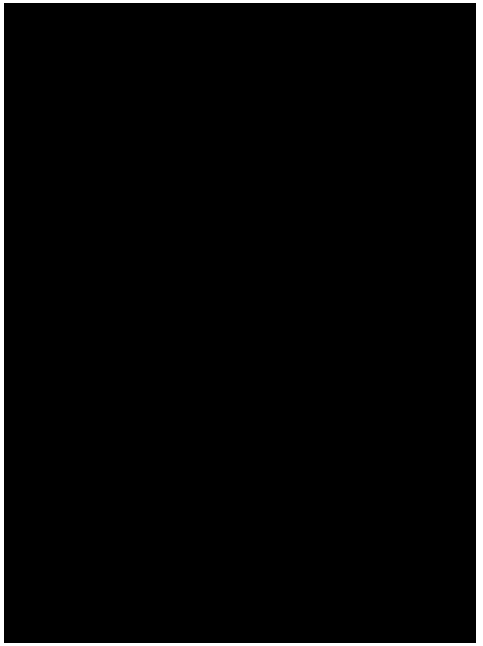
Collect X-ray images of the sample as you rotate it through 180°



Penetrating power

Multiple angles

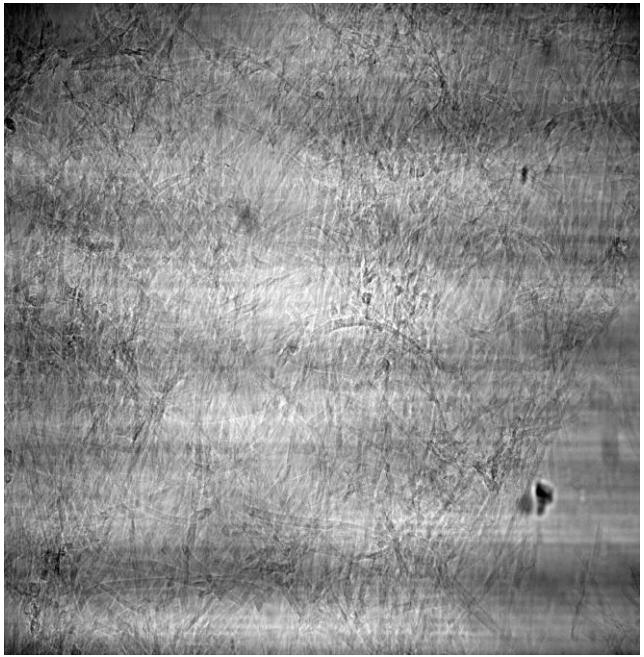
Use this series of images to “reconstruct” the 3D object



Courtesy of D. Parkinson (ALS)

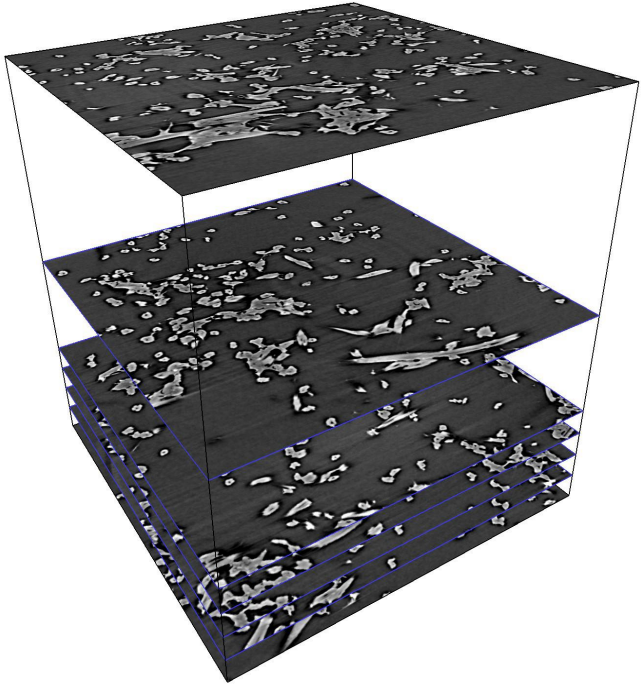
X-ray micro-tomography

X – Ray Projections



Reconstruction Software

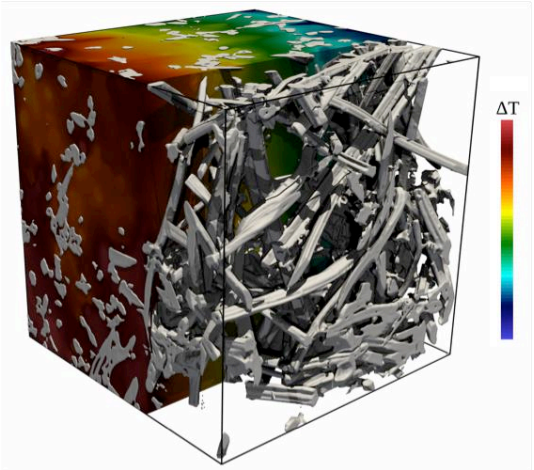
Reconstructed Image Stack



Characterize material micro-structure

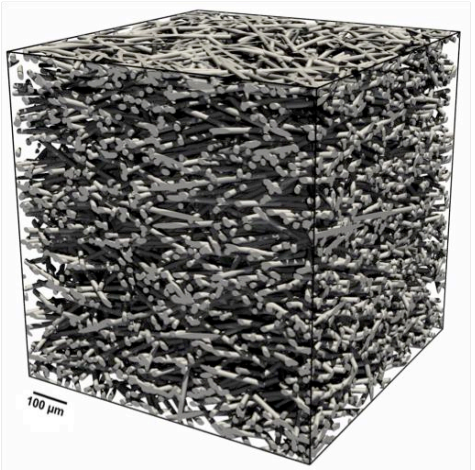
- Use of x-ray micro-tomography to characterize material micro-structure
- Determination of physical properties such as pore size, fiber diameter

Determine effective material properties and response



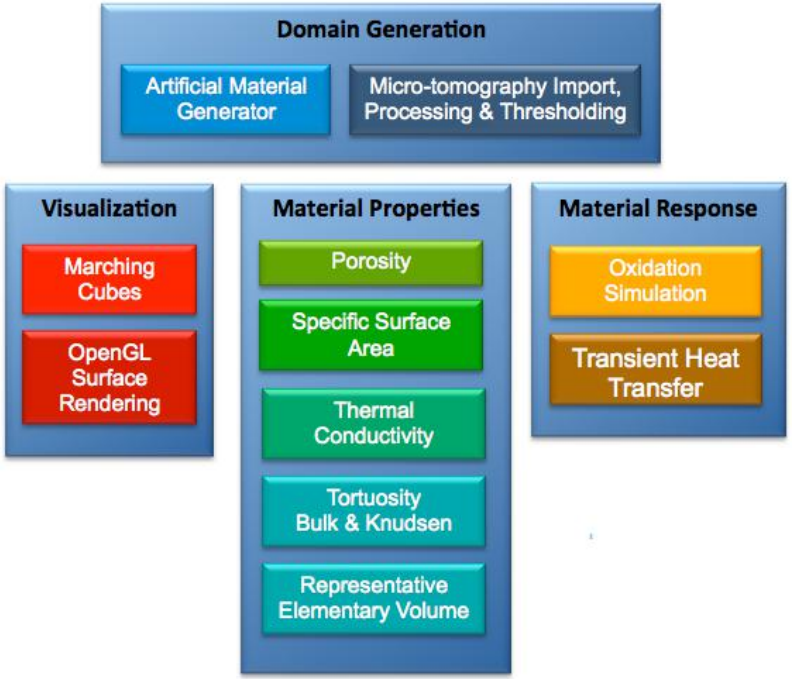
- Determination of material properties and response based on micro-structure
- Porosity, specific surface area, thermal conductivity, permeability, tortuosity

Material design from micro-structure



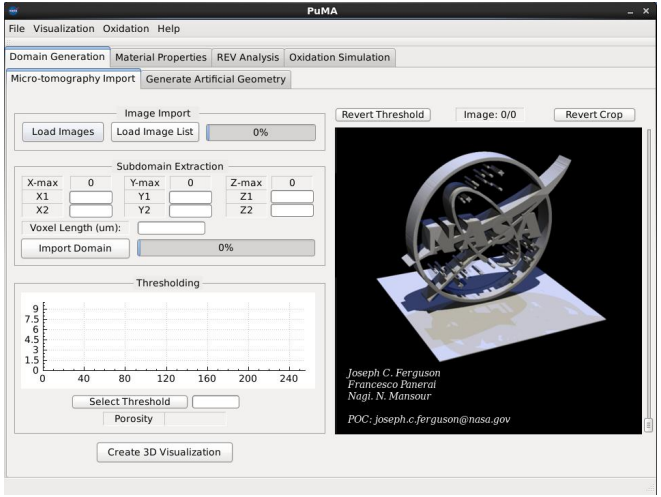
- Generation of artificial micro-structures
- Goal of fine-tuning material characteristics to meet design requirements

Porous Materials Analysis (PuMA)



Technical Specifications

- Written in C++
- GUI built on QT
- Visualization module based on OpenGL
- Parallelized using OpenMP for shared memory systems



Effective Material Properties

Porosity

- Based on the grayscale threshold
- Sum of all void voxels over the total volume

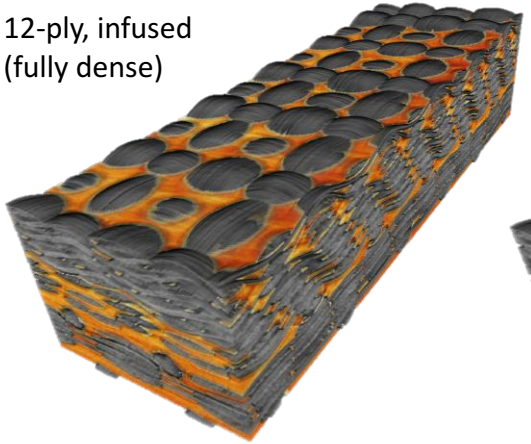
Specific Surface Area

- Based on the Marching Cubes algorithm
- Overall surface area computed as a sum of individual triangle areas

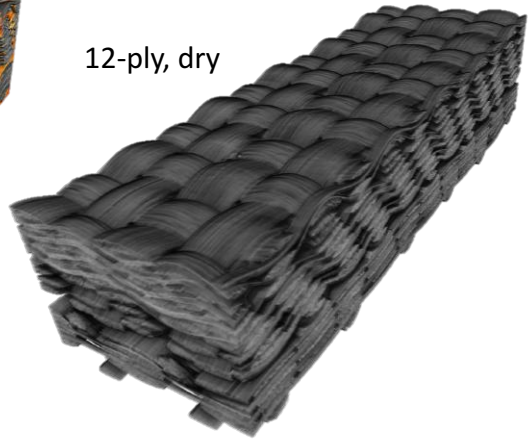
Effective Thermal Conducitivity

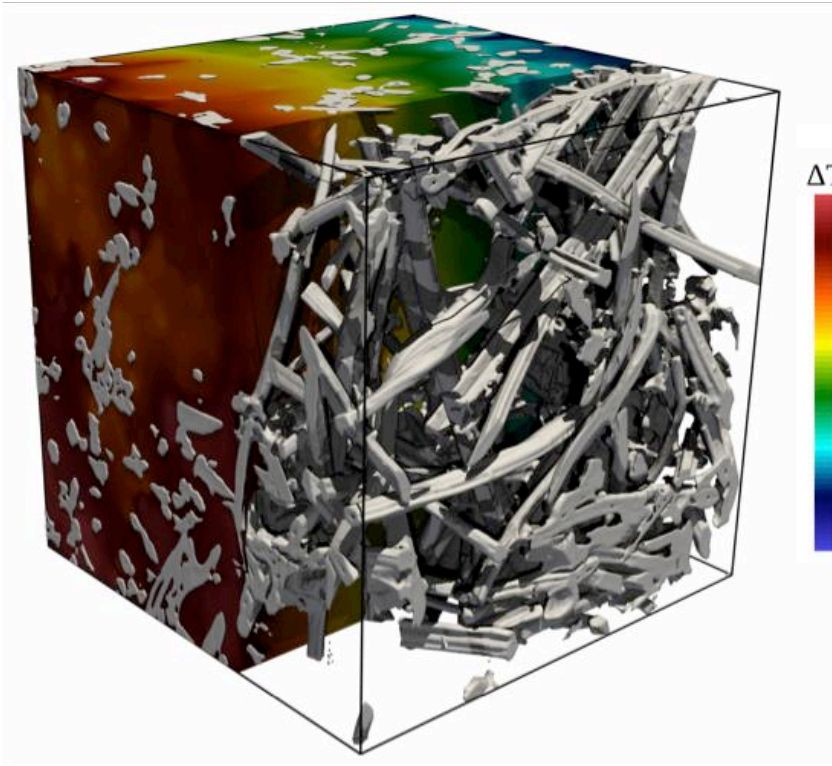
- Computes effective thermal conductivity using a finite difference method [Weigmann, 2006]
- BicGStab iterative method and FFTW used to solve linear system of equations [Sleijpen, 1993]
- Parallelized based on OpenMP
- Verified against complex analytical solutions

12-ply, infused
(fully dense)



12-ply, dry





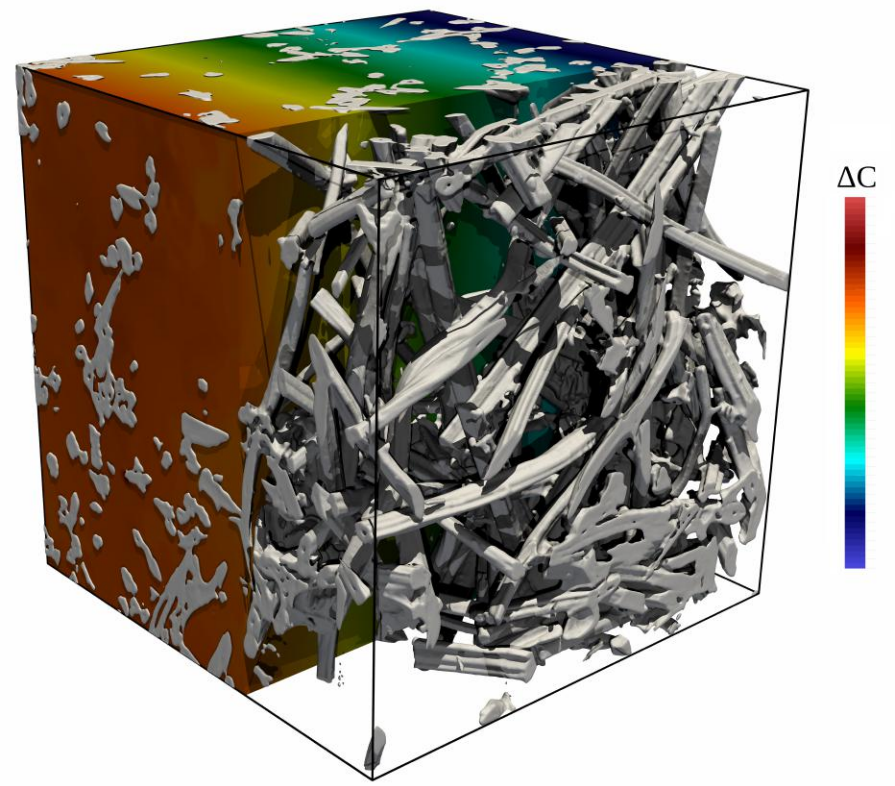
Diffusivity / Tortuoosity

Continuum

- Solves for effective diffusivity using a finite difference method

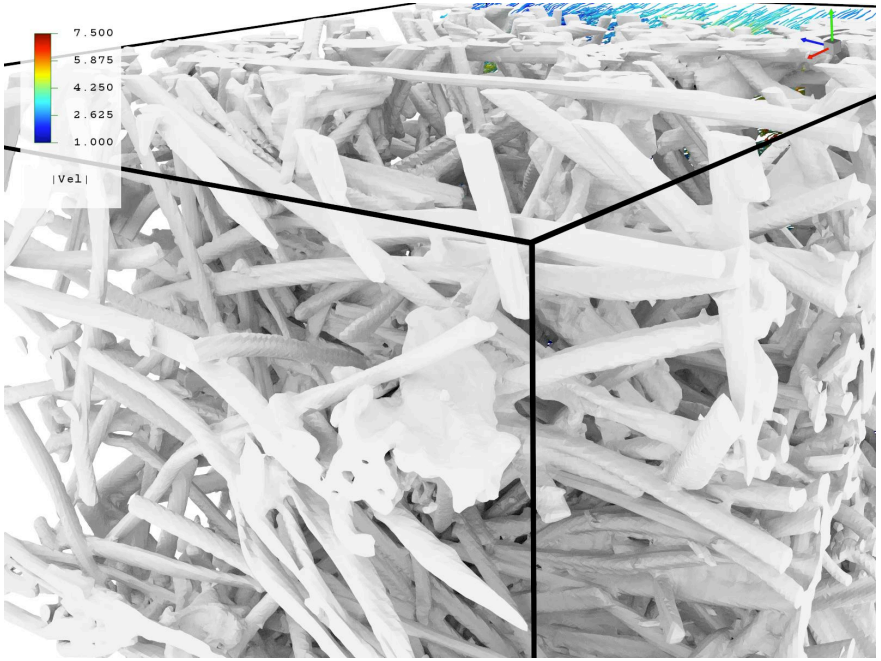
Transitional/Rarified

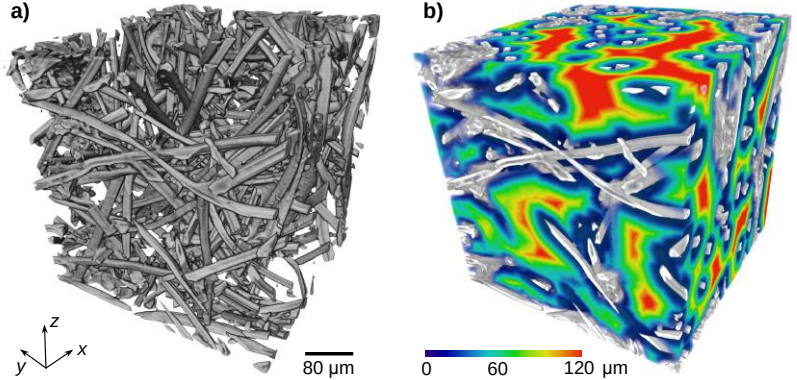
- Solves effective diffusivity through a random walk method
- Knudsen number is varied by changing molecular mean free path



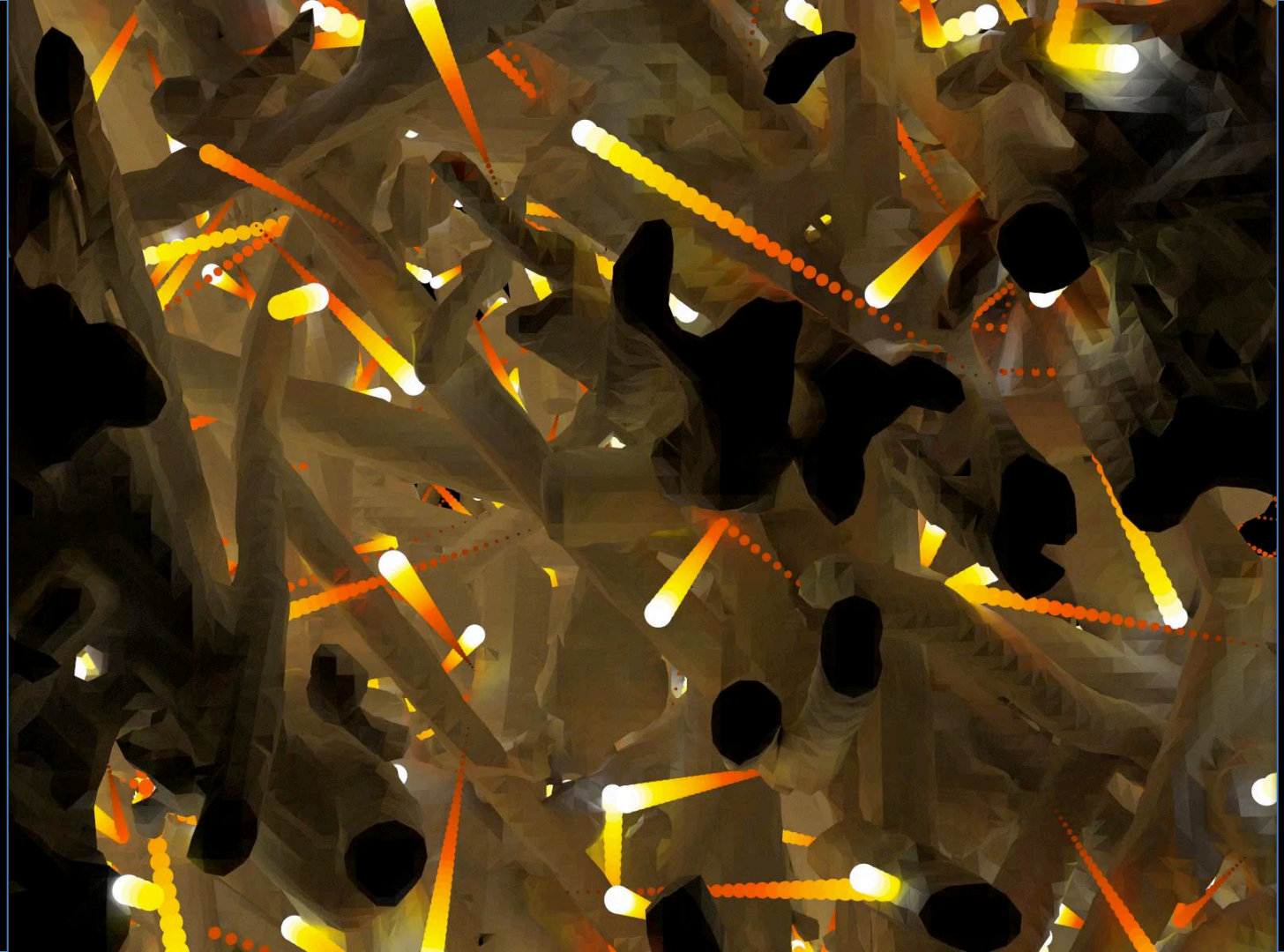
Permeability using DSMC

- Direct Simulation Monte Carlo (DSMC): probabilistic simulation method to solve the Boltzmann equation for finite Kn
- Simulates fluid flow using a particle-based approach with particle-particle and particle-surface interactions
- Ability to solve chemically reacting flows at high Knudsen numbers (where typical CFD is no longer valid)
- DSMC code: SPARTA (Sandia)



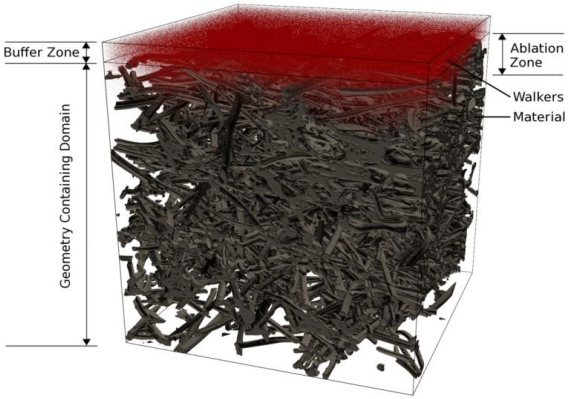


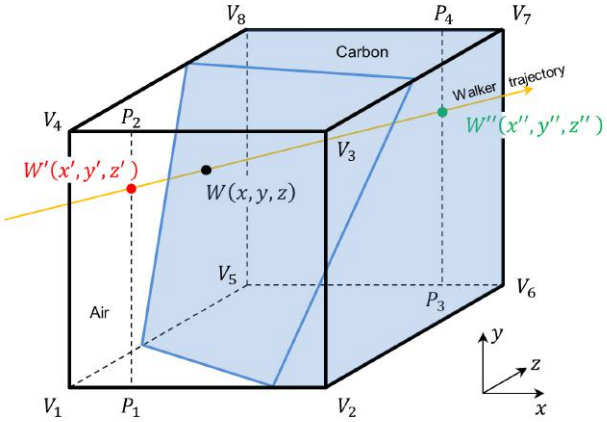
Borner et al., *Int J Heat Mass Transfer* (2016), in press

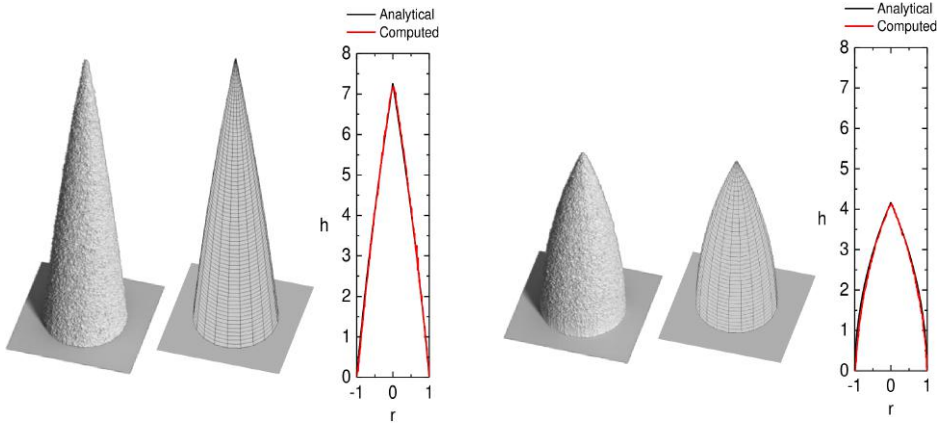


Micro-Scale Oxidation Simulations

- Particle-based oxidation method
- Diffusion simulated through random walks
- Collision detection with linear interpolation method
- Sticking probability method for material recession
- Verified against analytical solutions for single fiber

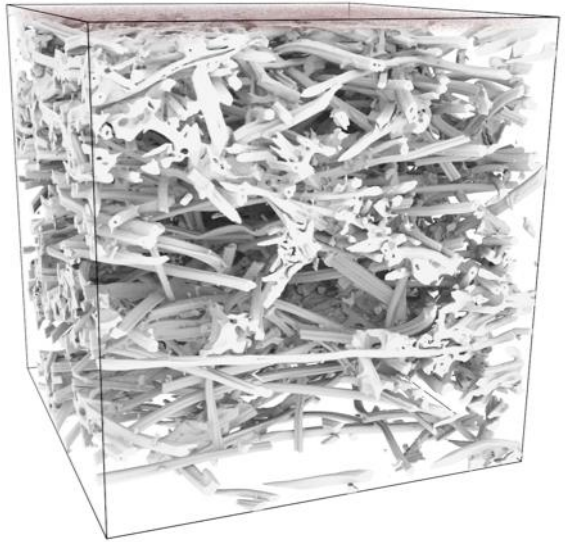


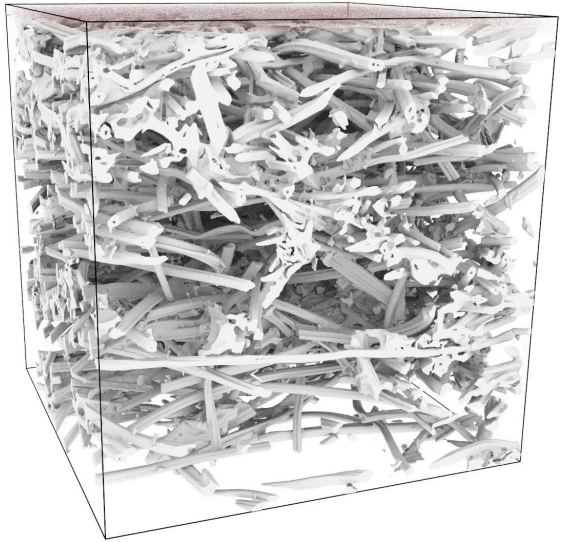


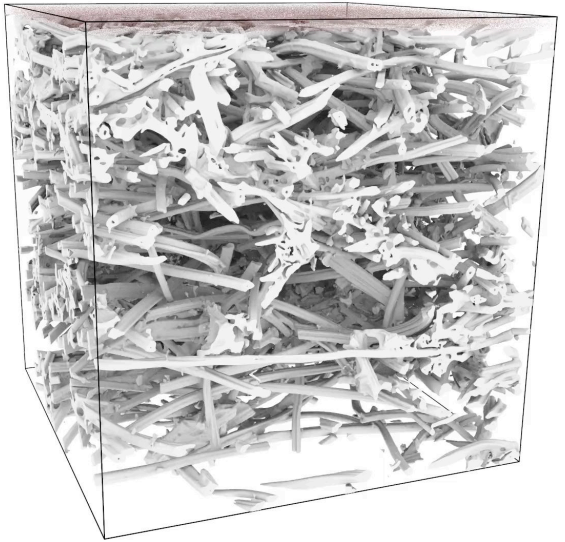


Ferguson et al., *Carbon* 96 (2016), 57-65

Micro-Scale Oxidation Simulations



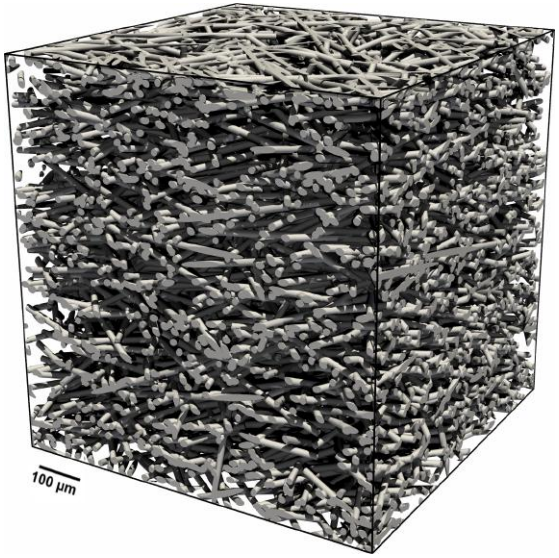




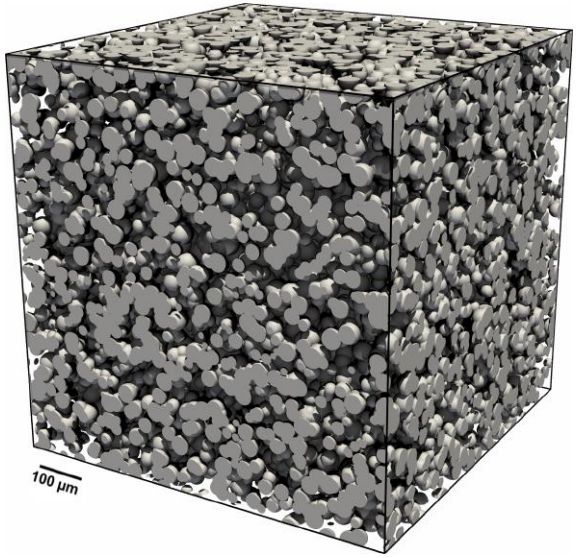
Ferguson et al., *Carbon* 96 (2016), 57-65

Material Generation

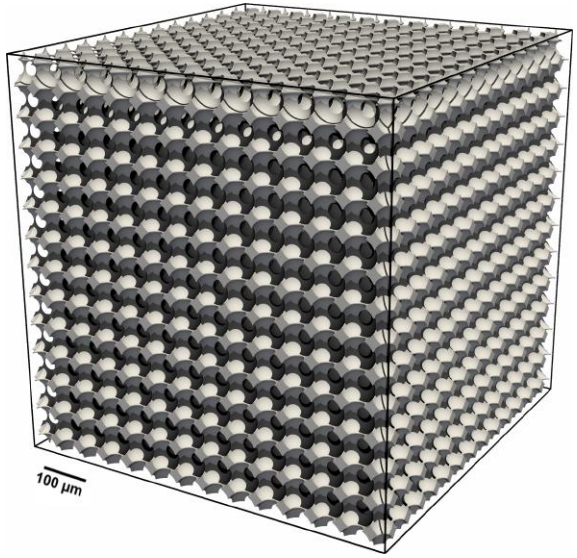
Random Fiber Structures



Packed Sphere Beds

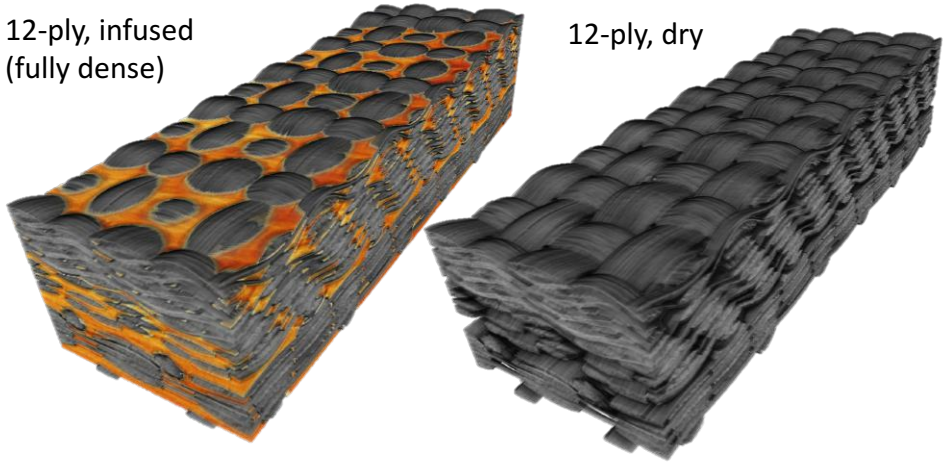


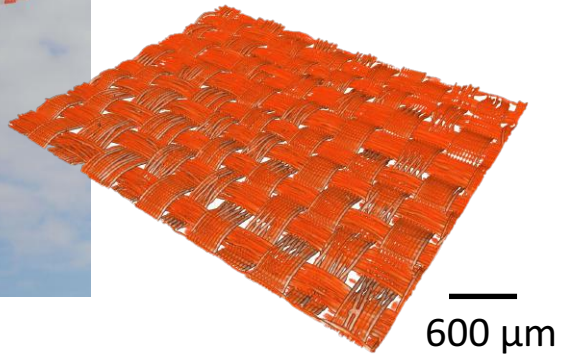
Periodic Foams



Conclusion and Outlook

- **Micro-tomography and simulations**
  - Help us developing TPS response modes
  - Enable predictive materials modeling
  - Support cheaper and faster material development
  - Impact not only Entry Descent Landing, but also other NASA's grand challenges:





Acknowledgements

- This work was supported by the Entry System Modeling project (M.J. Wright project manager) of the NASA Game Changing Development program.

- T. Sandstrom, C. Henze, D. Ellsworth, and B. Nelson for useful discussions during the development of PuMA and the parallelization of the oxidation model.

- A.A. MacDowell and D.Y. Parkinson are acknowledged for their assistance with tomography measurements.

- The Advanced Light Source is supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.